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Identification of L-Shell Transitions in M-shell Iron Ions in the Spectra of Capella and Procyon

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We studied HETGS observations of Capella and LETGS observations of Procyon observed by the *Chandra X-ray Observatory* in order to identify L-shell transitions of M-shell ions of iron, many of which also play an important role in the absorption features associated with spectra from active galactic nuclei. We have recently identified several Fe XVI L-shell transitions in spectra of Capella between 15 and 18 Å. With the help of laboratory measurements from the Livermore EBIT-I electron beam ion trap and very accurate calculations, we have now also identified Fe XV lines in the HEG and MEG spectra of Capella. Our analyses of the LETGS spectra of Procyon show that Procyon provides an even better opportunity for studying such iron lines. Procyon is much cooler than Capella and the abundance of lower charge states of iron, i.e., of M-shell iron ions, is much higher. We show that the 15 to 18 Å region of the Procyon spectrum contains lines from Fe XVII, Fe XVI, Fe XV, Fe XIV, and, possibly, Fe XIII.

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I. INTRODUCTION

Accurate wavelengths are a prerequisite for fitting astrophysical spectra and extracting the information contained in the superb spectra obtained with present-day instruments, such as the high-energy transmission grating spectrometer (HETGS) and the low-energy transmission grating spectrometer (LETGS) aboard the *Chandra* and the radial grating spectrometer on the *XMM-Newton* x-ray observatories[1]. Without accurate wavelengths, the fluxes from various lines, for example, may be incorrectly added in modeling spectra, resulting in faulty inferred parameters such as emission measures, temperatures, or densities.

L-shell transitions of M-shell ions have gained new prominence in astrophysics because they are observed in absorption spectra from active galactic nuclei[2,3]. The measurement of these lines in the laboratory has been difficult, making accurate calculations very important.

II. RESULTS

Fe XVI is the simplest M-shell ion, with only one valence electron in the M shell, and we have already reported measurements of its L-shell transitions[4]. These measurements were carried out using the electron beam ion trap facility at Lawrence Livermore National Laboratory. We have now begun to extend these measurements to the L-shell transitions of Fe XV and Fe XIV, as shown in Fig. 1.

In parallel, there have been theoretical developments to produce wavelengths that match those produced by laboratory measurements and required by astrophysical observations. A combination of the many-body pertubation theory (MBPT) method and the configuration-interaction (CI) method was used by Gu[5] and Gu et al.[6] to produce wavelengths of L-shell transitions in iron and nickel that were shown to be superior to earlier results using the CI method alone, as employed, for example, by the Hebrew University Lawrence Livermore Atomic Code (HULLAC)[7] or by the Flexible Atomic Code (FAC)[8]. In addition, the relativistic multi-reference Møller-Plesset (MR-MP) perturbation theory[9,10] has now been shown to produce exceptionally accurate wavelengths of iron L-shell transitions. In particular, these calculations were shown recently to produce results that are indistinguishable from the laboratory measurements[11].

The MR-MP method has now been extended to calculate L-shell transitions in Fe XV and Fe XIV in order to analyze the new laboratory data. An overlay of the theoretical spectra on to the experimental data is shown in Fig. 1. We find excellent agreement in most cases between theory and observation, which allows us to identify several Fe XV and some Fe XIV transitions in the laboratory spectra.

Using our calculated Fe XVI wavelengths from Beiersdorfer et al.[11], we examined the *Chandra* High Energy Grating and Medium Energy Grating observations of Capella (α Aurigae) to check for features that may be due to iron M-shell lines. We indeed found many unassigned features in the spectrum of Capella that correspond to the locations predicted Fe XVI lines (Fig. 2). Using our new identifications of Fe XV and Fe XIV, we have also

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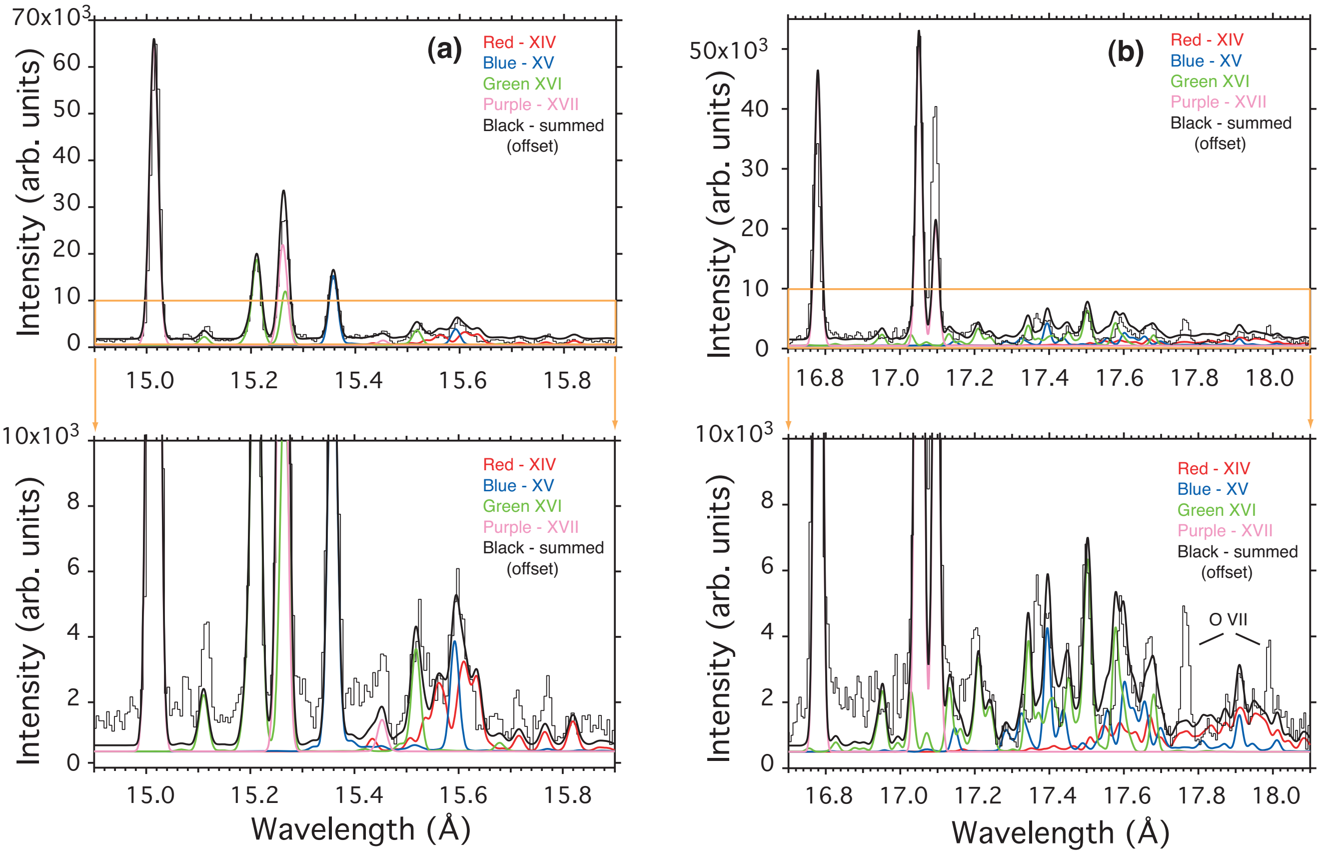

FIG. 1. Comparison of iron measurements with new calculations. (a) 14.9-15.9 Å region. (b) 16.7-18.1 Å region. The iron spectrum was taken with the Lawrence Livermore EBIT-I machine at a beam energy of 1.5 keV. Calculated lines are based on MR-MP (for wavelength) and FAC (for intensity). Calculated lines have been normalized to the strongest observed line in each charge state for each wavelength region; calculated intensities in the 17 Å region have been made several times larger than in the 15 Å region. Black trace for the sum of the calculated lines has been slightly offset to allow the constituent lines to be seen. Scale in bottom figures has been expanded to show the weaker lines.

searched for features from these charge states of iron in the Capella observations. We could only find one weak feature, which we believe corresponds to the strongest Fe XV line at 15.356 Å (see Fig. 2). We believe that Capella is too hot to identify further L-shell transitions of M-shell iron lines.

The spectra of stars cooler than Capella may contain more emission from lower charges states of iron M-shell ions. We have investigated this notion by looking at the spectrum of Procyon (α Canis Minoris), which is a much cooler star than Capella. In Fig. 3, we show the emission of L-shell iron near 15 Å of Procyon observed with *Chandra*'s LETGS. Although the resolution is poor and the noise in the spectrum is high, we can identify the well known Fe XVII line at 15 Å. It is accompanied by emission on its long-wavelength side, which extends to about 15.5 Å, as seen in Fig. 3. Using the spectral models we developed to fit our laboratory data shown in Fig. 1, we have fitted the Procyon observations. The fit of the Procyon observations requires flux from Fe XVI, Fe XV, and Fe XIV. Emission from even lower charge states of iron is probably also present, but cannot be ascertained given the high noise level in the observation. An observation of Procyon with the HETGS will be needed to to resolve the individual spectral features from Fe XVI, Fe XV, and Fe XIV near 15 Å. However, it is clear that the L-shell emission from M-shell iron ions contributes to the Procyon spectrum, and, by inference, it probably also contributes to the spectra of other cool stars. Thus, this kind of emission is much more prevalent than believed just a few years ago.

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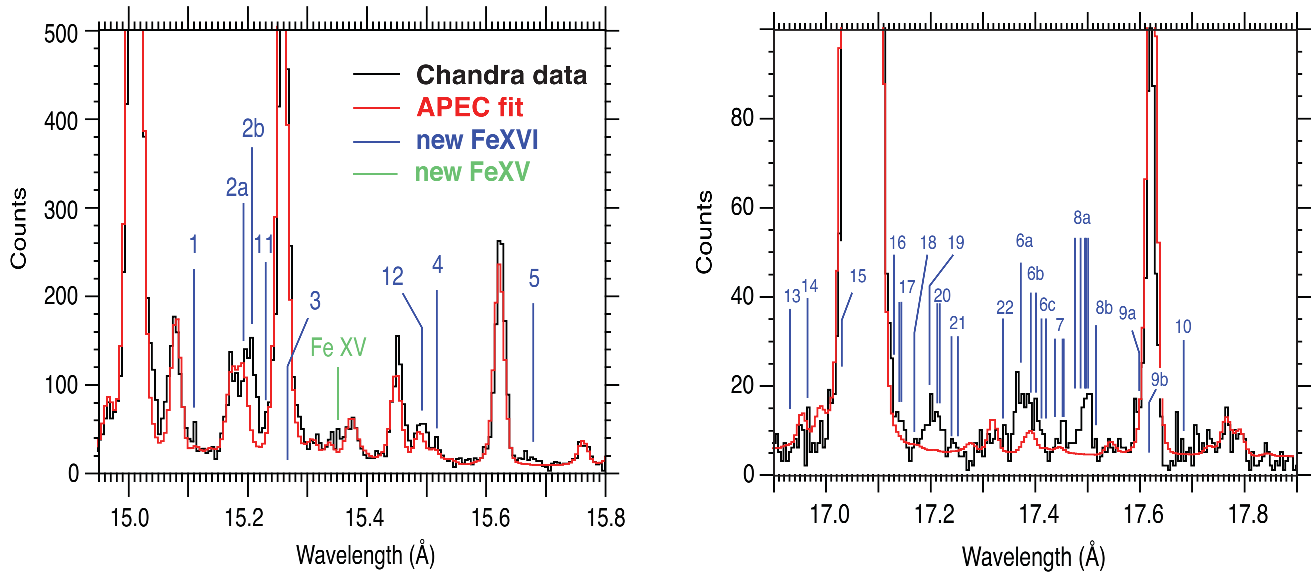

FIG. 2. MEG observation of Capella with newly identified iron lines. The plus order of observations totaling 298 ksec are co-added and shown by the black trace. Also shown in red is the modeled fit using the APEC database. New identifications of Fe XVI are shown in blue and account for most of the flux missing from the APEC model. The new identification of Fe XV is shown in green.

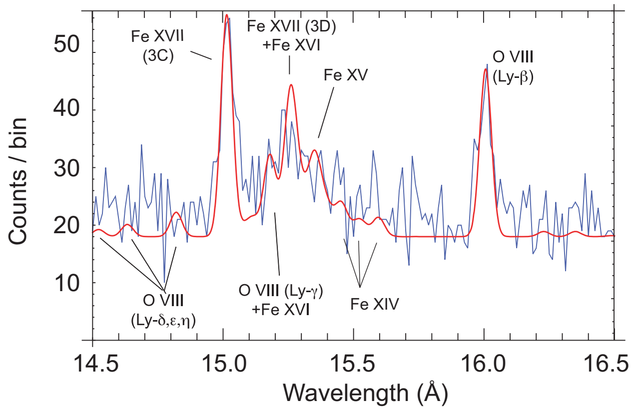

FIG. 3. LEGTS observations of Procyon in the 14.5 to 16.5 Å region with newly identified iron lines. Plus and minus orders of four observations totaling 280 ksec are co-added and shown by the blue trace. Also shown is a modeling calculation of the collisionally excited lines of Fe XVII, Fe XVI, Fe XV, Fe XIV, and O VIII in the red trace. The intensity of the Fe XVI DR satellite lines was not included in the model. Although resolution is low and noise is high, Fe XVI, XV, and XIV appear to be present.

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